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Record high damselfish recruitment at Rottnest Island, Western Australia, and the potential for climate-induced range extension

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ABSTRACT

Three-decades of observations of tropical fish recruitment on the south coast of Rottnest Island, Western Australia (WA), have indicated that settlement of two tropical damselfish (*Abudefduf sexfasciatus* and *A. vaigiensis*) peaks each autumn with the seasonal strengthening of the Leeuwin Current (LC). Historically these fish have not bred at Rottnest Island or at other adjacent coastal locations although an active breeding population exists at the Houtman Abrolhos Islands some 330 km to the north. Record levels of recruitment in early 2011 followed extremely strong southward advection in the LC accompanied by unprecedented high water temperatures associated with a marine heat wave. Settlement numbers the following year were almost as high, again associated with a very strong LC and high water temperatures, while 2013 saw lower but still above average recruitment. Against a background of gradual ocean warming along the WA coast, one of the world's 30 hotspots for increasing ocean temperature, the potential for these species to establish a breeding population at Rottnest Island is explored by comparing the water temperatures during the presumed spawning period at the Abrolhos Islands with those at Rottnest Island together with winter temperatures and the abundance of what are believed to be mature *Abudefduf* successfully over-wintering at Rottnest Island. "The results indicate that establishment of a breeding population at Rottnest Island does not appear to be limited by water temperatures, and raises the question as to why a breeding population does not already exist as the settlement habitat appears very similar to that at the Abrolhos Islands.

1. Introduction

The southward penetration of tropical marine species down the west coast of Australia has long been associated with the warm tropical waters of the Leeuwin Current. Early biological surveys noted the mixed tropical/temperate species distribution along the coast (Saville-Kent, 1897; Michaelsen, 1908; Dakin, 1919; Maxwell and Cresswell, 1981) but it was only in the 1970s that newly-developed oceanographic techniques such as current meter (Cresswell et al., 1989), thermal satellite imagery (Legeckis and Cresswell, 1981) and satellite-tracked drifting buoys (Cresswell, 1980) enabled (Cresswell and Golding, 1980) to formally identify and name the Leeuwin Current (LC). Both the LC and the coastal summer counter-current, the Capes Current (Pearce and Pattiaratchi, 1999; Gersbach et al., 1999), play a major role in the transport and distribution of pelagic marine larvae (Muhling and Beckley, 2007; Muhling et al., 2008), with distinctive seasonal and cross-shelf variations in the larval fish assemblages along the south-western continental shelf.

As a direct result of the LC, tropical fish and invertebrates are transported southwards into temperate latitudes, including a number of tropical reef fish species which have been monitored over the past three decades at Rottnest Island (Fig. 1) by surveys that represent one of the longest-running quantitative marine biological observations undertaken off Western Australia. In particular, the larval/juvenile phases of two damselfish species (*Abudefduf sexfasciatus*, the Scissor-tail Sergeant, and *A. vaigiensis*, the Indo-Pacific Sergeant) have been observed to arrive at Rottnest Island each austral autumn at the time the LC traditionally strengthens (Hutchins, 1991, 1994; Hutchins and Pearce, 1994; Pearce and Hutchins, 2009).

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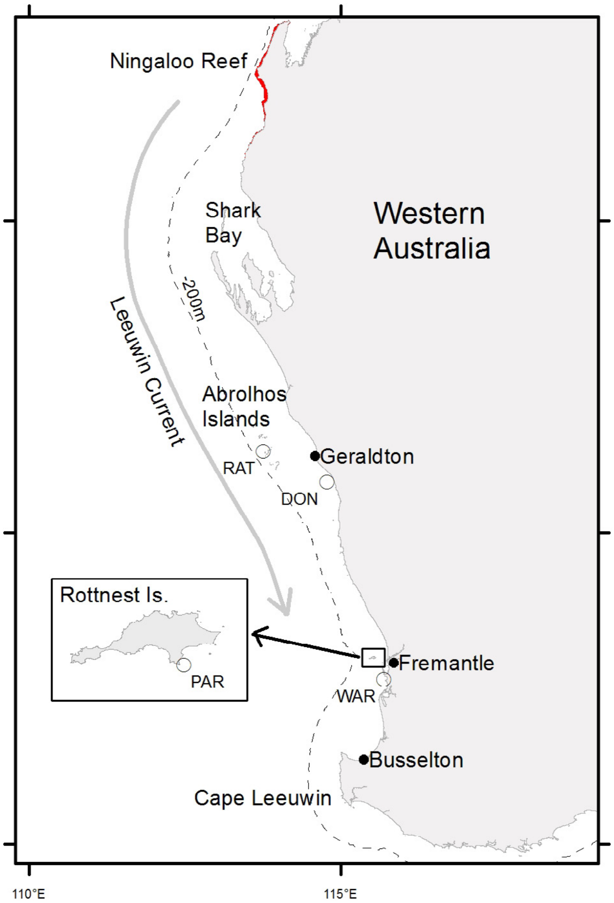

Fig. 1. Map of Western Australia showing the locations mentioned in the text and locations of *in situ* temperature measurements (open circles): RAT = Rat Island, DON = Dongara, PAR = Parker Point, WAR = Warnbro Sound.

The progressive change in species composition with latitude southwards is well illustrated by the series of reef fish surveys undertaken along the west coast between 1976 and 1993 by Hutchins (1994; also see update in Hutchins, 1997a). He grouped the observed species into tropical, subtropical and warm-temperate categories, some being endemic to the west coast. The proportion of tropical fish species fell from almost 100% at Ningaloo in the north to 5% at Cape Leeuwin in the south and to virtually zero on the south coast (Fig. 2), while the proportion of southern warm-temperate species correspondingly rose from zero at Ningaloo to 80% at the Capes and to 95% on the south coast. Subtropical species which comprise the majority of the State's endemics (Hutchins, 1994) were most abundant between Kalbarri and the Capes, contributing to the recognition of the west coast as a global "centre of endemism" (Roberts et al., 2002). The open points on Fig. 2 represent the offshore islands of the Abrolhos group (29°S) and Rottnest Island (32°S), clearly demonstrating the higher proportion of tropical species (and correspondingly lower proportions of temperate species) nearer to the edge of the continental shelf compared with the adjacent mainland coast. The tropical/warm-temperate species ratios at these offshore islands match those at the mainland coast some 2° latitude (∼220 km) further north, because of both the southward transport and the warmer water out in the LC compared with the nearshore region. This is particularly true during the winter months when the current is flowing most strongly and the nearshore waters are cooling as a result of heat loss to the atmosphere (Pearce et al., 2006a; Zaker et al., 2007).

Abudefduf species are widely distributed along the WA coast, being more abundant, both in species diversity and numerically, in more northern waters and tailing off towards the south in line with most tropical species (Fig. 2). In his wide-ranging series of coastal fish surveys undertaken between 1975 and 1993, Hutchins (1994) listed the ten most abundant fish species at 12 locations between Ningaloo (∼22°S) and the south coast. Along the mainland coast, *A. sexfasciatus* was abundant as far south as Shark Bay (Fig. 1) and *A. bengalensis* was relatively common as far south as the Kalbarri–Geraldton region (Fig. 1). At the Abrolhos Islands, however, Hutchins' (1997a) more detailed review of the fish communities showed that four species were present at the three southern island groups (Wallabi, Easter and Pelsaert) with *A. sexfasciatus* being classed as "abundant" (in fact, the 6th most common species in the archipelago), *A. vaigiensis* "frequent", *A. bengalensis* "occasional" and *A. sordidus* "rare".

Hutchins' results are largely echoed in the unpublished listings from the more recent Reef Life Survey online dataset (http://reeflifesurvey.imas.utas.edu.au/portal/home, accessed July 2015). *A. bengalensis* was commonly sighted along the mainland coast as far south as Shark Bay with stragglers at the Abrolhos Islands, whereas *A. sexfasciatus* and *A. vaigiensis* were common both at the Abrolhos Islands and Rottnest Island. Neither of these species were reported from the mainland coast south of Shark Bay.

This paper examines the ocean currents and water temperatures associated with record high recruitment pulses of both *A. sexfasciatus* and *A.vaigiensis* which occurred during the "marine heat waves" experienced off south-western Australia in 2011, 2012 and to a lesser extent 2013 (Pearce et al., 2011b; Pearce and Feng, 2013; Caputi et al., 2014). The term "recruitment" is used here in

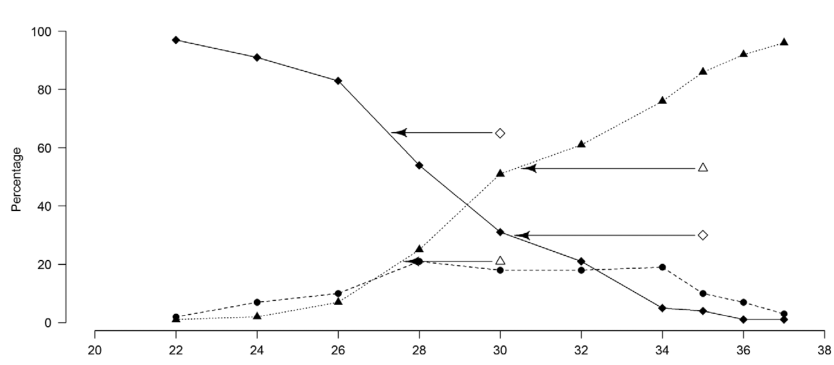

Fig. 2. Relative proportions of tropical (diamonds, solid line), warm-temperate (triangles, dotted line) and subtropical (circles, dashed line) reef fish species along the Western Australian coast between Ningaloo at ∼22°S and Cape Leeuwin at ∼34°S, and continuing east along the south coast to 127°E (modified from Hutchins, 1994). For plotting convenience, the three south coast sites have been coded as latitudes 35°S, 36°S and 37°S. The lines link the coastal sites, and the offshore islands (Abrolhos at 29°S and Rottnest at 32°S) are represented by the larger open symbols, the arrows pointing to the mainland latitude where the same species proportion occurs.

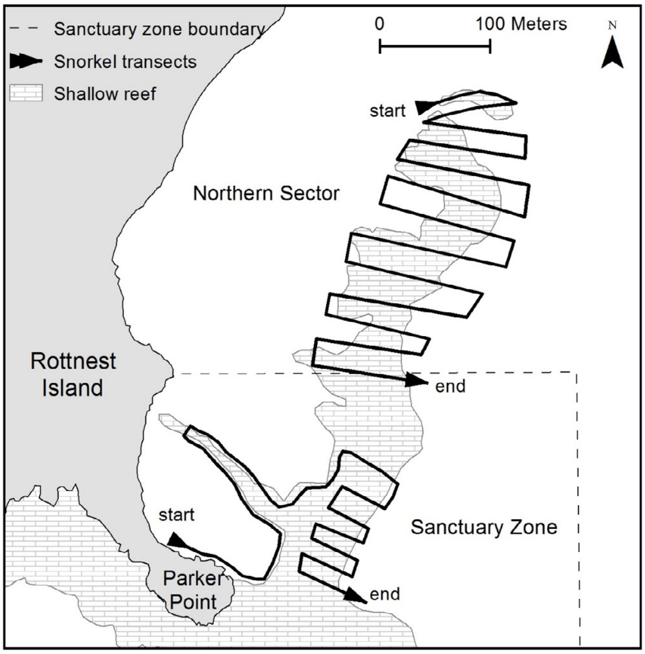

Fig. 3. The Sanctuary Zone and Northern Sector survey zones east of Parker Point showing the approximate track swum by the observer during the fish surveys; the shaded shallow area is Pocillopora Reef.

relation to the arrival and settlement of late-stage larvae or recently metamorphosed juveniles of both species at Rottnest Island. During the unprecedented summer 2011 heat wave event, which was associated with an intense *La Niña event*, the LC was flowing strongly (and seasonally early) in conjunction with record high water temperatures (Pearce and Feng, 2013; Feng et al., 2013). The high recruitment levels were followed by unusually large numbers of adults above the assumed length at maturity successfully overwintering, which raised the question of whether there was potential for southward range extension of the two damselfish species, allowing establishment of breeding populations at Rottnest some 330 km to the south of the nearest known breeding location.

2. Materials and methods

Rottnest Island is located in the Southern Indian Ocean 18 km offshore from Fremantle on the lower west coast of WA (Fig. 1). It is an A-class Marine Reserve due to its significant heritage and biodiversity values and is a popular recreational destination for nearby Perth. Parker Point (Fig. 3), on the south-east coast, is a major headland that is protected from north west and westerly storm events, that itself shelters the shallow beds of *Pocillopora* coral from the prevailing south westerly swells. Other off-shore reefs extending off Parker Point add further protection from ocean swells.

2.1. Fish observations

Observations of fish have been made in the coastal waters of Rottnest Island since 1977 (Hutchins, 1977), with some gaps due to diver availability and weather (Table 1). Because of their relatively large numbers and easy identification, two damselfish species, i.e. *A. sexfasciatus* and *A. vaigiensis*, have received particular attention and are the focus of this paper. As early surveys around Rottnest Island had indicated that the settlement of tropical fishes was best observed at Parker Point, more comprehensive observations were undertaken in that area from 1995, comprising both more frequent surveys and a broader scope of observation.

During these surveys, *Abudefduf* were counted and visually grouped by length. Recently arrived pelagic recruits of both species appear silvery but quickly develop dark bars after settlement while individuals that are transported below rafts of *Sargassum* can arrive with the darker colouration (Pearce and Hutchins, 2009). The two smallest length groups were categorised as (a) very small fish with pelagic colouration (TL 15–23 mm) (hereafter termed "larvae" to represent newly-arriving pre-settlement fish), and (b) recently-arrived and metamorphosed "very small juveniles" (TL 25–36 mm) (Pearce and Hutchins, 2009). These two smallest length classes represent new recruits arriving at the Island, equivalent to the "Class 1" fish used by Russell et al. (1977). Table 2 shows the classes and range of lengths of fish observed by Pearce and Hutchins (2009). Length–age relationships derived for *A. vaigiensis* (David Booth, unpublished data) suggest that the ages of the "larvae" ranged from about 10 to 26 days, the latter approximating the pelagic larval duration (PLD) for the species (Wellington and Victor, 1989; Thresher et al., 1989) while those for the "very small juveniles" were up to about 50 days.

During each survey, a diver (BH) swam a single preset pattern covering Pocillopora Reef in the Sanctuary Zone (SZ) east of Parker Point (Fig. 3), visually counting the number of fish in each size category for a range of selected species (Hutchins and Pearce, 1994). A total of 208 surveys were conducted between January 1995 and December 2013 at nominally monthly intervals (Table 1) and extra observations were made during the peak autumn recruitment periods. Complementary surveys were often carried out in the adjacent "Northern Sector" (NS) immediately to the north of Pocillopora Reef (Fig. 3). Because of the extreme range between the highest and lowest (zero) counts, the square root of the counts was used in some of the plots.

To derive a consistent monthly time-series for direct comparison with the monthly oceanographic variables, the maximum number of fish in two smallest length classes observed in each calendar month in the SZ were calculated as described in Pearce and Hutchins (2009); observations from the NS were not included in the monthly series as they were less regular and so would have biased the totals. While these visual methods may not have the technological sophistication of more modern video-based techniques such as Baited Remote Underwater Videos (BRUVs, e.g. Watson et al., 2010), the smaller post-settlement juvenile sizes which can be counted visually are not visible in the video imagery. Thus, these visual methods have provided a relatively simple way of obtaining a comprehensive and consistent survey of selected species using a single experienced diver over a long period, and have been widely used in similar fish studies off the east coast of Australia (Booth et al., 2007; Figueira and Booth, 2010; Beck et al., 2014).

2.2. Oceanographic measurements

Three environmental variables which have traditionally been used as indices of the main oceanographic processes along the Western Australian continental shelf (Pearce and Phillips, 1988) are:

(a) the Southern Oscillation Index (SOI, a measure of the strength and phase of *El Niño*/Southern Oscillation (ENSO) events). Monthly values of the SOI from 1980 to 2013 were obtained from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/current/soihtm1.shtm, accessed February 2014).

(b) Monthly-averaged sea levels for Fremantle (FMSL) have been used as a convenient index of the "strength" of the LC (Pearce and Phillips, 1988; Feng et al., 2003). Monthly sea levels for 1984 to mid-2013 were downloaded from ftp://ilikai.soest.hawaii.edu/woce/m175.dat. Following the closure of this site

Table 1
List of enhanced fish surveys ($n = 208$) in the Sanctuary Zone off Parker Point per month since 1995, updated from Pearce and Hutchins (2009). Surveys in the Northern Sectors were less regular.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	2	2	3	1	1	3	1	1	1	2	1	1
1996	1	1	2	1	2	1		1		2	1	1
1997		1	3	2	2	2	1	1	1		1	
1998	1	1	3	2	2	2	2	1	1		1	1
1999	1	1	3	2	2	1	3	1	1	1	2	1
2000	1	2	1	2	1	2		1	1	1	2	1
2001	1	1	3	4	1	2	1	2		2	1	
2002	1	1	2		2				1		1	
2008			1		1	1		1	1		1	1
2009	1	2	3	3	2	1	2		1	1	2	1
2010	2	1	2		2	1		1	1			1
2011	2	2	3	1	3	1	1	2	2	1	1	1
2012	2	2	3	2	1	1	1	1	1	1	1	1
2013	1	1	2	1	1	1		2		1		1

Table 2
Classes, descriptions and observed ranges of total lengths of *Abudefduf*.
Source: Modified from Pearce and Hutchins (2009).

Class	Description	Total length TL mm
a	Larvae (pelagic colouration)	15–23
b	Very small juvenile	25–36
c	Small juvenile	40–55
d	Juvenile	65–77
e	Large juvenile	80–100
f	Sub-adult (about to mature)	110+

Table 3
Dates of first observations of each category of each species in either the Sanctuary Zone or the Northern Sectors at Parker Point. January/February arrivals have been bolded.

Year	*Abudefduf sexfasciatus*		*Abudefduf vaigiensis*	
	Larvae	Juveniles	Larvae	Juveniles
1995	11 Mar	21 Mar	21 Mar	27 Mar
1996	**29 Feb**	9 Apr	9 Apr	9 Mar
1997	24 Mar	24 Mar	17 Apr	15 Apr
1998	29 Mar	14 Apr	14 Apr	14 Apr
1999	7 Mar	7 Mar	12 Mar	12 Mar
2000	**18 Jan**	**18 Jan**	**12 Feb**	14 Mar
2001	6 Mar	13 Mar	17 Apr	12 Apr
2002	20 Mar	16 May	28 Mar	16 May
(gap)				
2008	30 Mar	30 Mar	7 May	
2009	6 Mar	25 Mar	6 Apr	15 May
2010	9 Mar	9 Mar	20 Jun	20 Jun
2011	**9 Feb**	**23 Feb**	**9 Feb**	**23 Feb**
2012	**8 Feb**	**8 Feb**	**21 Feb**	17 Mar
2013	**31 Jan**	7 Mar	**14 Feb**	

in late 2013, daily data for the remaining months of 2013 were downloaded from http://uhslc.soest.hawaii.edu/data/download/fd (accessed January 2016) and the monthly means calculated, and pre-1984 monthly averaged sea levels were obtained by the author in the 1990s directly from the original National Tidal Centre at Flinders University in Adelaide.

(c) Satellite-derived sea surface temperature (SST) obtained from the Reynolds OISST dataset (Reynolds and Smith, 1994: http://climexp.knmi.nl/select.cgi?id=someone@somewhere&field=sstoi_v2 which commenced in 1982. The monthly temperatures are on a 1 degree latitude/longitude grid (equivalent to a nominally 100 km block), and have been extracted for the Abrolhos Islands region and Rottnest Island. Water "skin" temperature is typically within about 0.3 K of the bulk temperature (Donlon et al., 2002), but is dependent on factors such as the solar insolation, wind speed and ocean conditions.

To avoid bias from the extreme conditions experienced in 2011 and 2012 (and to a lesser extent 2013), the long-term seasonal sea level and temperature cycles were derived for the period 1980 to 2010, and monthly sea level and temperature anomalies were then calculated by subtracting these mean annual cycles (and in the case of sea level, the long-term rising sea level trend) from the monthly values. For a longer-term perspective, HadISST1 monthly temperatures for the Abrolhos Islands and Rottnest Island from 1990 to 2013 were obtained from http://climexp.knmi.nl/select.cgi?id=someone@somewhere&field=hadisst1 (accessed Jan 2016). The finer-scale local variability embedded within the monthly ∼100 km averages is derived from hourly water temperatures measured using *in situ* temperature loggers. Onset TidBit Model TBI32-05+37 loggers and/or Hobo Model UA-001-64 loggers have been used at Rat Island in the Abrolhos Islands group, Dongara on the adjacent mainland coast, Parker Point on the south coast of Rottnest Island and Warnbro Sound on the mainland coast adjacent to the island. Three of these loggers commenced in 2002 while the Parker Point logger was installed in early 2010. Daily- and monthly-averaged temperatures were derived from the hourly values.

3. Results and discussion

3.1. *Abudefduf* settlement at Rottnest Island

Recruitment of both *Abudefduf* species between 1995 and 2013 followed a strong seasonal pattern as well as showing high inter-annual variability (Figs. 4 and 5). There was consistency in the generally progressive increase and then fall in settlement over successive surveys (rather than isolated "spikes"), increasing confidence in the survey data and indicating that the recruitment pulses extended over weeks rather than days. On the occasions that observations were made in the NS, the abundance of both size categories there (Fig. 4(b)) was overall much lower than in the smaller SZ area (Fig. 4(a)) except for the heavy settlement periods when the population in the NS rose sharply.

The seasonal cycle was strongly defined: from virtually zero in mid-summer (January), settlement generally rose sharply in March/April to reach a peak in April/May (Pearce et al., 2011a) before falling away again over the remainder of the year (Fig. 5). Juvenile abundances were particularly high in 1995, 1999, 2000 and the marine heat wave period 2011 to 2013 and were generally associated with a strong Leeuwin Current and anomalously high water temperatures during strong *La Niña* events.

The earliest recruits were usually sighted was in March in most years, notably for *A. sexfasciatus*, (Table 3), however, in 2000 and between 2011 and 2013 the first recruits arrived as early as January or early February. Settlement in summer 2011 was the highest observed, commencing in early February and peaking relatively late through May and into early June, and relatively

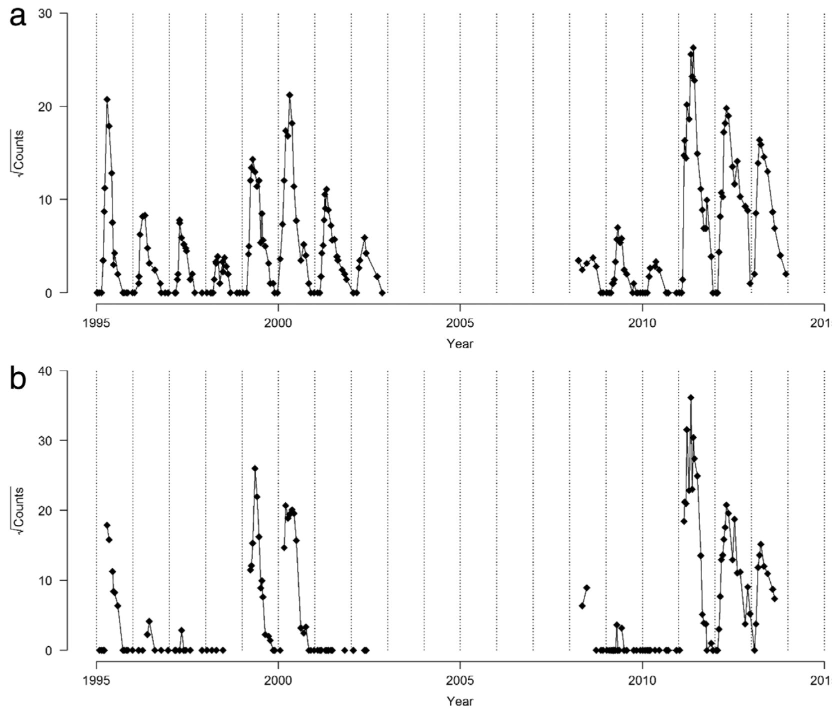

Fig. 4. Numbers of recruits (15–36 mm) for both *Abudefduf* species combined in (a) the Sanctuary Zone and (b) the Northern Sector between 1995 and 2013. Note the square root scale used on the *y*-axis. There were no observations between 2003 and 2007.

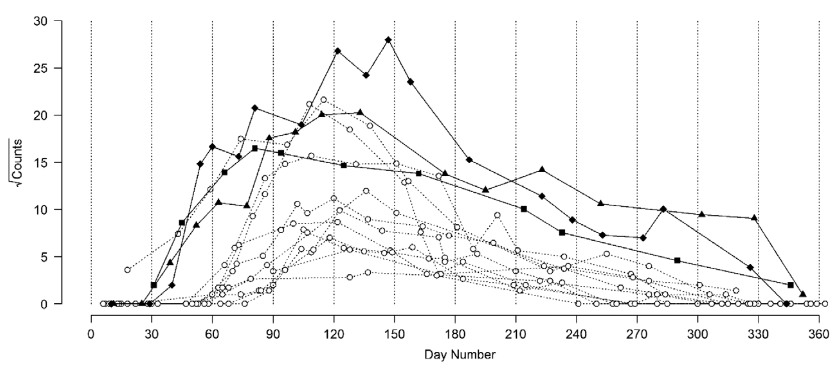

Fig. 5. Square root of the total counts of small juvenile (<36 mm) Abudefduf in the Sanctuary Zone from 1995 to 2010 (open symbols, dashed lines) and the 3 year period: 2011 (filled diamonds), 2012 (filled triangles) and 2013 (filled squares). The vertical lines represent 30-day "months".

high numbers of juveniles continued to arrive and settle until the end of the year (Fig. 5). Numbers were also high (and early) the following summer of 2012 but matched previous "good" years, and by 2013 the settlement was subsiding back towards more "normal" levels. Apart from the early arrivals between 2011 and 2013, it is noteworthy that the settlement in those years remained relatively high for the rest of the year until December.

3.2. Oceanographic processes

The historically close relationship between the strength of the LC, sea surface temperature and *El Niño/La Niña* events (Pearce and Phillips, 1988; Feng et al., 2003) is demonstrated by the annual mean values of the Southern Oscillation Index (SOI), the linearly de-trended Fremantle sea level (FMSL) and the Reynolds OISST anomaly over the past three decades (Fig. 6(a)). Between 1980 and 2013, there were a number of strong ENSO events defined by low SOIs (1982, 1987, a lengthy episode 1991–1994, and 1997) and equally intense *La Niña* events with high SOIs (1988/89, 1996, 1999/2000, 2008 and the record 2010/11 episode). The *La Niña* periods were generally associated with high sea levels, implying relatively strong LC flow and correspondingly warmer tropical water transported southwards. The correlation between the annual FMSL anomaly and the SOI over the 34 year period was 0.734 ($p < 0.001$) and between the annual FMSL and SST anomalies was 0.768 ($p < 0.001$).

The annual settlement of the two *Abudefduf* species in the Sanctuary Zone at Rottnest Island also revealed high levels of inter-annual variability (Fig. 6(b)), with greatly enhanced recruitment during the *La Niña* years 1999/2000 and the period when the marine heat wave developed in 2010/2011. The enhanced recruitment in 1995 preceded the *La Niña* of 1996 (the SSTs were however relatively high in 1995 despite average sea levels), and 2008 saw only moderate recruitment (number of observations were somewhat low in early 2008 compared with most years, Table 1), despite relatively high sea levels and SST. Embedded within each year, however, were some significant shorter-term environmental variations which are explored using the monthly oceanographic indices and the associated recruitment between 2008 and 2013, particularly comparing the three years prior to the

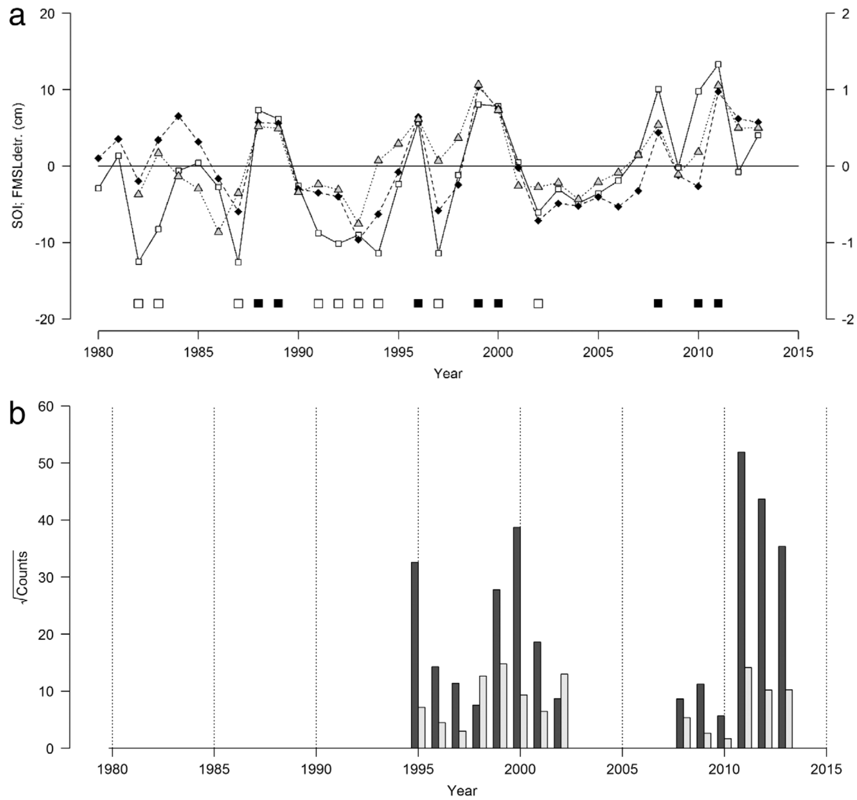

Fig. 6. (a) Annual mean values of the Southern Oscillation Index (left axis: SOI, solid line, open squares), de-trended Fremantle sea level anomaly (left axis: FMSLdtre, hatched line, filled diamonds) and the Reynolds OISST anomaly for the block covering Rottnest Island (right axis: SSTanom, dotted line, open triangles) over the past three decades. The open squares at the figure base were the *El Niño* years (defined here as SOI < -5) and the filled squares La Niña years (SOI > 5). (b) Total annual counts of small juvenile *A. sexfasciatus* (dark grey) and *A. vaigiensis* (light grey) in the Sanctuary Zone, derived from the monthly time-series for 1995–2013 (see text). Note the square root scale on the *y*-axis.

heat wave of 2011 with the settlement during and immediately after the marine heat wave.

Overall, the LC followed the traditional pattern of flowing most strongly during the late autumn and winter months of 2008, 2009, 2010 and 2013 (Fig. 7(a)), but in 2011 the strongest southward current was in summer and in 2012 the flow again strengthened as early as January and persisted until June. These were both periods with extremely strong *La Niñas* (Fig. 7(b)) and resulted directly in the record high SSTs of early 2011 and 2012 which reached unprecedented levels of almost 25 °C off Rottnest Island in February/March 2011 and were above 23 °C in the following two summers (Fig. 7(a)). The monthly SST anomaly reached 2.7 °C above the long-term summer average in February 2011 and was well above 1.5 °C the following January/February before returning towards more normal levels in summer 2013. Further north at the Abrolhos Islands, the SST was > 26.5 °C in February/March 2011 for these monthly-averaged SSTs and anomalies over an area of 100 × 100 km; in shallower nearshore waters, hourly temperature logger measurements yielded daily mean temperatures of over 26 °C off Rottnest Island and 29 °C at the Abrolhos Islands, corresponding to anomalies from the long-term mean of ∼3 °C near Rottnest Island and 5 °C at the Abrolhos Islands (Pearce and Feng, 2013). These high surface temperatures were driven both by strong southward advection of warm tropical water in the LC combined with high air–sea heat flux (Pearce and Feng, 2013; Feng et al., 2013) partly associated with conditions much further north which were subsequently defined by Feng et al. (2013) as "Ningaloo *Niño*" events.

The exceptionally strong and warm southward flow in the early months of 2011 to 2013 was believed to be largely responsible for the enhanced *Abudefduf* settlement at the time (Fig. 7(a)). In addition to the recruitment at Rottnest Island, the 2011 marine heat wave had other repercussions for the marine life along the south-western Australian continental shelf. There were fish kills involving invertebrate and finfish species along the mid-west coast as well as unusual sightings of tropical marine species in temperate southern waters and even along the southern coast of WA (Pearce et al., 2011b; Smale and Wernberg, 2012; Wernberg et al., 2012; Moore et al., 2012; Pearce and Feng, 2013; Caputi et al., 2014). Included in these unusual visitors were new recruits of a further two *Abudefduf* species; *A. bengalensis* and *A. sordidus* sighted at Rottnest Island, and a single *A. sordidus* adult was spotted near Parker Point in mid-2013 (BH unpublished observations). More noteworthy, however, was the first-ever sighting of an *A. sexfasciatus* larva at the Underwater Observatory at Busselton jetty (Fig. 1) some 200 km south of Rottnest Island (Pearce et al., 2011b). The ∼3 cm fish was first spotted in late March 2011 and remained *in situ* until a storm passed through in early May. The following March 2012, again with a strong Leeuwin Current, saw the arrival of two individuals between 2–3 cm in length, the latter growing to about 5 cm when it was last seen in June 2012 (http://www.busseltonjetty.com.au/wp-content/uploads/2014/03/Unusual-UWO-visitors.pdf, accessed December 2015; and Busselton Jetty unpublished records, courtesy Sophie Teede).

3.3. Implications for potential range extension to Rottnest Island

While there have been very few observations of *Abudefduf* breeding activity in WA, Hutchins (1997b) documented breeding populations of *A. sexfasciatus* and *A. vaigiensis* at Shark Bay and the Abrolhos Islands. It appears that the only location where

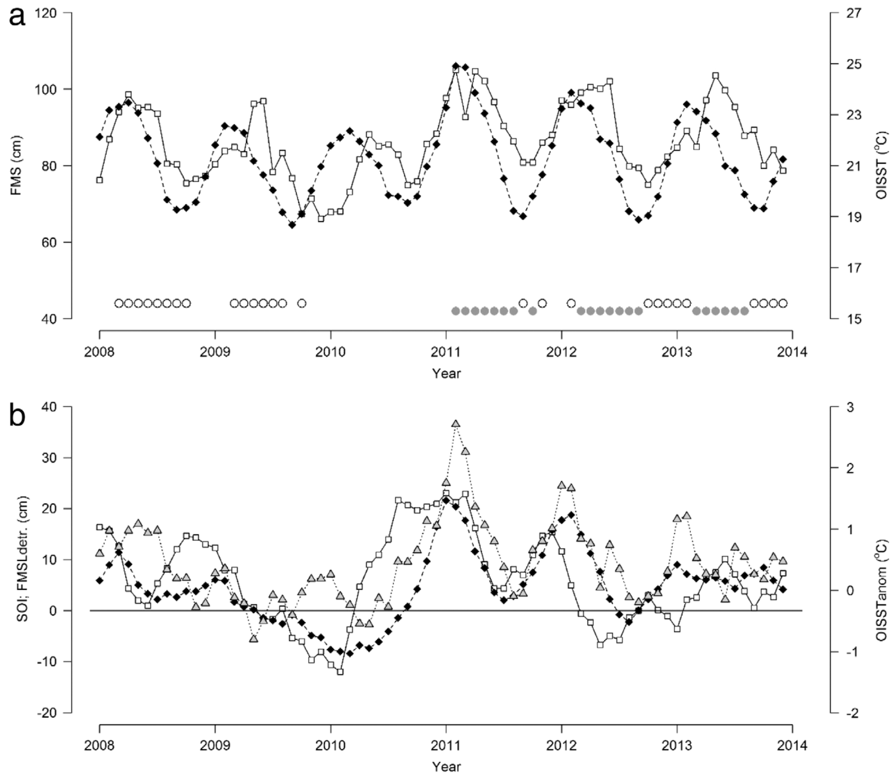

Fig. 7. (a) Monthly mean Fremantle sea level (left axis: solid line, open squares) and the Reynolds OISST for the 1 degree block at Rottnest Island (right axis: hatched line, filled diamonds) for 2008 to 2013. The symbols along the bottom represent the monthly counts of category small juvenile *Abudefduf* in the Sanctuary Zone: open circles $<$ 100 fish, grey filled circles $>$ 100 fish. (b) Monthly SOI (smoothed with a 3-month moving average to minimise clutter, solid line, open squares) and monthly anomalies of Fremantle sea level (unsmoothed; hatched line, solid diamonds) and OISST (unsmoothed; dotted line, filled triangles).

active nesting behaviour has been directly observed (and filmed) has been in Exmouth Gulf by Whisson and Hoschke (2013, and unpublished observations) during brief visits in June 2008 and November 2011. Over the three decades of fish surveys at Rottnest Island, no *Abudefduf* breeding activity has ever been witnessed nor have egg nests or nest guarding behaviour been sighted.

The progressive rise in water temperatures off south-western Australia, an area that has been identified as one of 30 global ocean hotspots of increasing temperature (Fig. 8; Pearce and Feng, 2007; Hobday and Pecl, 2014) and the greatly enhanced settlement levels at Rottnest Island since 2011 raise the question whether a breeding population could become established there. That question is addressed here as three sub-questions:

(a) What are the temperature thresholds for *Abudefduf* spawning and survival?
(b) How do the water temperatures at Rottnest Island compare with those at the Abrolhos Islands?
(c) Do sufficient adult *Abudefduf* survive the winter temperatures at Rottnest Island to provide potential breeding stock?

3.3.1. Temperature thresholds for Abudefduf spawning and survival

Before examining the temperature records for the Abrolhos Islands and Rottnest Island, it is necessary to establish the temperature limits within which the species spawn and the over-wintering survival threshold. This information was derived from the literature and from temperature measurements available at the (few) spawning observations off WA and from the assumed spawning events at the Abrolhos Islands.

No information about the spawning environment for *A.sexfasciatus* or *A.vaigiensis* is available in the literature, so studies of the closely-related Caribbean sergeant major *A. saxatilis* (Allen et al., 1978) were used as a proxy. With *A. saxatilis*, spawning can occur at any time of year (Prappas et al., 1991), with spawning events lasting for a few days every 2–3 weeks (Foster, 1987). The eggs hatch after 4–5 days (according to Foster, 1987; Fishelson, 1970) although Shaw (1955) found 6–7 days at an ambient temperature of 24 °C.

Local observations of breeding populations of *Abudefduf* spp. have been made at a few locations off south-western Australia. At the time of breeding at the Abrolhos Islands in February and May 1994 (Hutchins, 1997b), monthly-averaged water temperatures derived from hourly temperature loggers were 23.0 °C and 23.8 °C respectively (Department of Fisheries unpublished data); during the May 1995 survey in Shark Bay (Hutchins, 1997a), water temperatures ranged from 22.7° to 25.8 °C. Both spawning behaviour and egg nests were observed in north-western Exmouth Gulf in June 2008 and November 2011, and small (∼2 cm) fish were sighted in October 2008 and June 2009 (implying very recent spawning, Hoschke & Whisson unpublished data): measured water temperatures were respectively 23.3 °C, 25.7 °C, 23.4 °C and 22.5 °C (Hoschke & Whisson unpublished data).

As new recruits of *A. sexfasciatus* and *A. vaigiensis* arrive at Parker Point virtually throughout the year, it may be assumed that spawning must have occurred at the Abrolhos Islands 3–4 weeks earlier, based on a week or so for the eggs to hatch and then the ∼3 week PLD for the larvae to be transported to Rottnest Island. Back-calculation of the previous month's temperatures at the Abrolhos Islands for each observed arrival at Rottnest Island (Fig. 9) yields water temperatures ranging from 19° to 27 °C for each of the two species with high levels of recruitment associated with water temperatures above 23 °C. These match the water temperatures during Hutchins' (1997a) surveys in 1994/1995 listed above, as well as the direct breeding observations at Exmouth between 2008 and 2011.

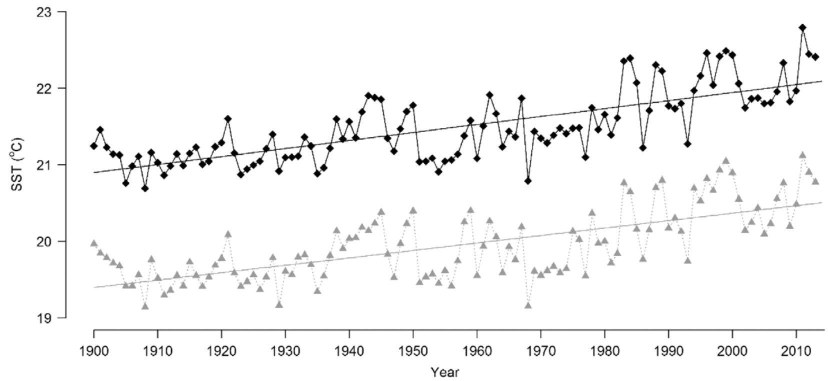

Fig. 8. Annual mean HadISST1 sea-surface temperatures at the Abrolhos Islands (upper graph) and Rottnest Island (lower graph) between 1900 and 2013. The long-term trend lines are shown, with equal slopes of 0.10 °C/decade.

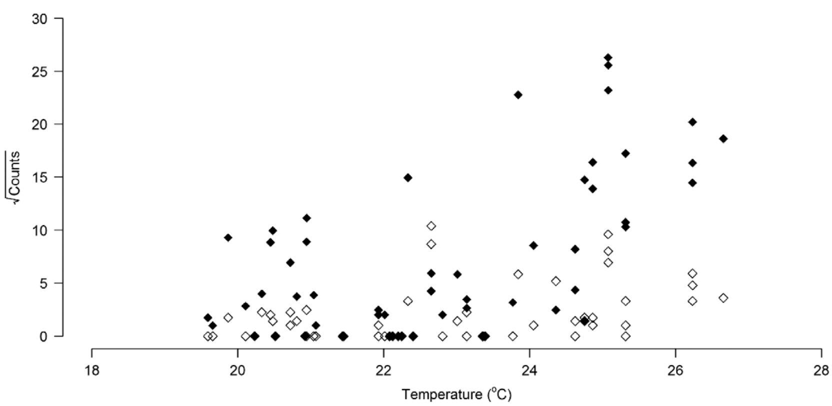

Fig. 9. Scatter-plot of the monthly recruitment (square root) of small juvenile *A. sexfasciatus* (solid diamonds) and *A. vaigiensis* (open diamonds) in the Sanctuary Zone at Parker Point between 1995 and 2013 against the monthly-averaged temperature logger measurements at the Abrolhos Islands from the previous month.

The over-wintering survival of *Abudefduf* at Rottnest Island will depend on a number of factors, including water temperature. In field studies off the east coast of Australia, Figueira et al. (2009) and Figueira and Booth (2010) found there was almost complete mortality of *A. vaigiensis* at average winter temperatures below 17 °C (although laboratory fish could survive down to 15 °C—Booth et al., 2011), and there were no survivors of *A. sexfasciatus* below average winter temperatures of 18 °C. A lower limit of 18 °C is therefore assumed as the over winter survival threshold here for Rottnest Island.

3.3.2. Water temperatures at Rottnest Island and the Abrolhos Islands

Long-term SSTs indicate that the overall mean water temperature at Rottnest Island is ∼1.5 °C cooler than that at the Abrolhos Islands (Fig. 8) although there has been a high level of matching inter-annual variability at the two locations. Periods of relatively lower temperatures have been followed by periods of accelerated warming, explaining why studies of the rate of temperature rise using different time-periods have sometimes conflicting results. Using the overall long-term trend of ∼0.1 °C/decade, it would take about 150 years for Rottnest Island to have a similar temperature regime to that presently at the Abrolhos Islands.

A more reliable assessment of the suitability of Rottnest Island for both survival and reproduction of *Abudefduf* species can be gained from local hourly temperature logger measurements. Over the 12 years of available measurements, monthly mean temperatures at Rat Island in the Abrolhos group never fell below 19 °C (Fig. 10(a)). There were fewer measurements at Parker Point (Fig. 10(b)) but the winter temperatures there are supported by seven years of satellite-derived SSTs (validated using temperature loggers) which also showed a mean winter trough of about 19 °C (Pearce et al., 2006b). At the adjacent mainland coastal locations of Dongara and Warnbro Sound (Fig. 1), however, winter temperatures were generally substantially lower than at the offshore island sites, and at Warnbro Sound in fact fell well below the 18 °C winter survival threshold, likely explaining the general absence of *Abudefduf* spp. along the mainland coast near Perth.

The monthly temperatures mask the shorter-term variability which is displayed in the daily mean temperatures. At Rat Island, the daily temperature was always above the assumed *Abudefduf* survival threshold (Fig. 11(a)), but at Parker Point there were a few days between June and September (during 2010) when the water was below 18 °C (Fig. 11(b)) although the level of resulting mortality for short term temperature falls is unknown.

3.3.3. Overwintering survival of potential spawners at Rottnest Island

Prior to the summer 2011 marine heat wave, the numbers of larger fish greater than 75 mm (TL) observed during the surveys were comparatively small while following the event there was a marked surge in their abundance (Fig. 12). This higher level of abundance was sustained through the following two winters during which the water temperature at Parker Point was above the 18 °C survival threshold.

On this basis, with adequate survivorship of sexually mature fish over 2 years and water temperatures at Parker Point above minimum temperatures at which spawning occurs at the Abrolhos Islands for most of the year (19 °C), it would appear that local *Abudefduf* breeding activity could take place at Rottnest Island and if ongoing represent a southward range extension from the present

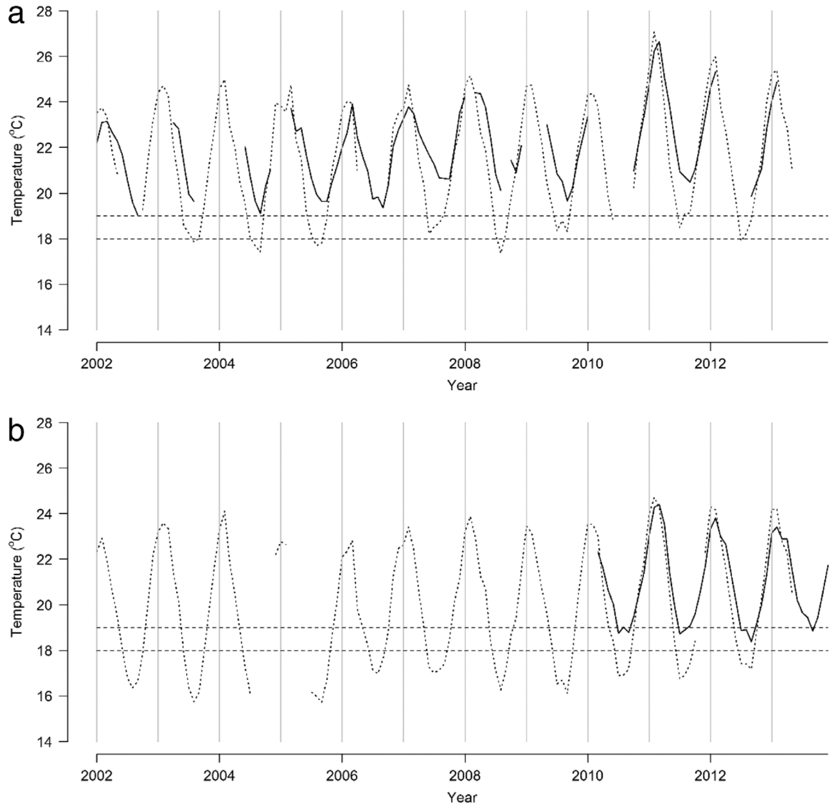

Fig. 10. Monthly mean temperatures from temperature logger measurements at (a) Rat Island (solid) and Dongara (dashed), and (b) Parker Point (solid) and Warnbro Sound (dashed). The straight lines at 18 °C and 19 °C represent the assumed minimum temperature thresholds for survival and spawning respectively.

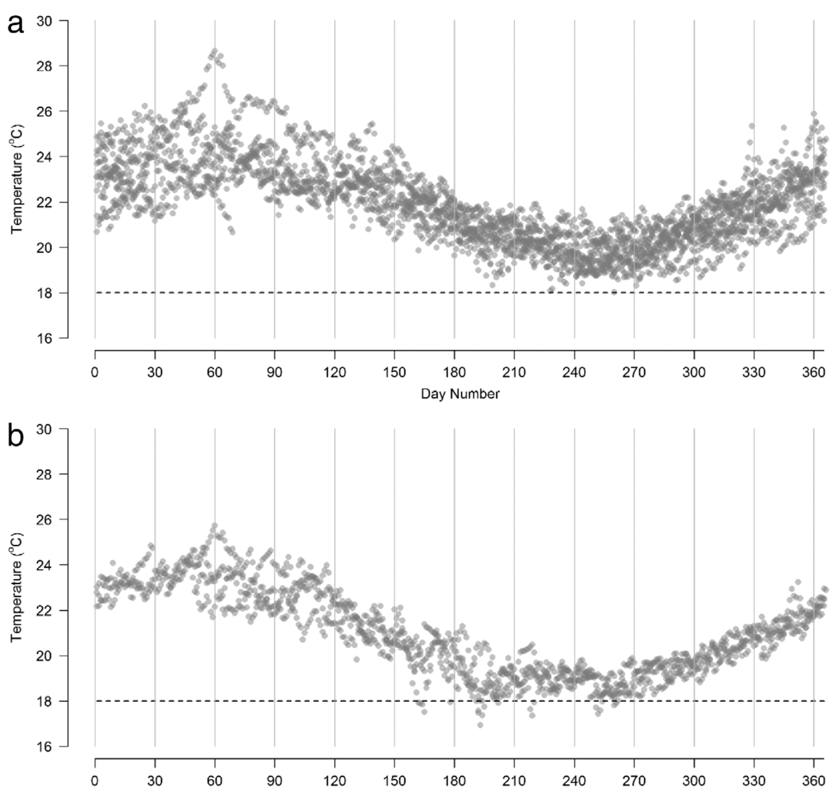

Fig. 11. Daily mean temperatures from temperature logger measurements at (a) Rat Island (2002–2014) and (b) Parker Point (2010–2014). The straight lines at 18 °C represent the assumed minimum temperature thresholds for survival. For convenience, the *x*-axis has been divided into 30 day "months".

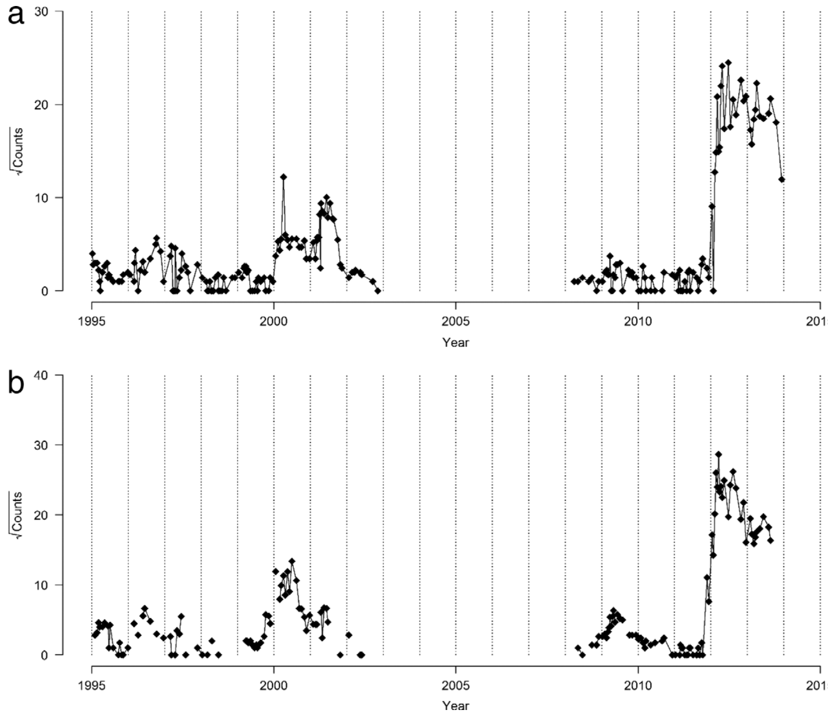

Fig. 12. Numbers of larger fish > 75 mm (TL) for both *Abudefduf* species combined in (a) the Sanctuary Zone and (b) the Northern Sector between 1995 and 2013. Note the square root scale used on the *y*-axis because of the extreme range in settlement numbers. There were no observations between 2003 and 2007.

larval source at the Abrolhos Islands. However, as pointed out by Feary et al. (2014), some species do not appear to extend their range for a variety of (often unknown) environmental factors and life history traits, despite climatic conditions apparently becoming more favourable for such a shift. While the oceanographic conditions at Rottnest Island (primarily water temperature) appear favourable for *Abudefduf* spawning and survival and the benthic habitat appear to be equally so, biological factors such as suitable and abundant food (affecting the numbers and condition of the potentially spawning adults), growth rates, predation and habitat competition (Feary et al., 2014) can still play an important role in whether spawning will occur and can therefore be defined as a range extension. A related study of the fate of three nearshore, and two inshore tropical species that were transported south during the marine heat wave, and settled into the coastal marine habitats of the waters off metropolitan Perth has revealed that juveniles of all five species were able to successfully overwinter. However, only individuals of the two inshore species were able to survive until maturity and breed. It is suspected that in addition to suitable SST, the availability of extensive preferred habitat at these southerly locations contributed to this success (Lenanton et al., in preparation).

4. Conclusions

The record high temperatures associated with the exceptionally strong (and early) LC during the strong *La Niña* event in early 2011 resulted in record recruitment of *A. sexfasciatus* and *A. vaigiensis* at Rottnest Island. Recruitment in the summer of 2012 was also very high (again in response to a seasonally early and strong LC) but by 2013 conditions were returning to more typical levels. This study re-iterates the value of having long-term monitoring of both biological and oceanographic observations to enable (unpredictable) extreme events to be investigated and put in perspective.

A trend of progressive temperature rise associated with global warming together with increasing pulses of high recruitment, generally during *La Niña* periods when regional water temperatures were above average, and the over-wintering survival of larger fish suggests the possibility of a southward range extension of these two species to Rottnest Island. As the fish are rarely sighted along the mainland coast south of the Abrolhos Islands in contrast with the well observed abundances at the Islands and at Rottnest Island, this would represent a quantum southward advance of some 300 km. It would also separate the Rottnest Island recruitment from the present larval supply at the Abrolhos Islands and effectively de-couple the LC transport link.

Although a range of other normally tropical species were sighted well south of their typical ranges during the summer 2011 heat wave (Pearce et al., 2011b) including first observations of a number of tropical fish at Rottnest Island (Caputi et al., 2014), such vagrant sightings were not viewed as "genuine" range extensions. Prior to the recent marine heat wave, mud crab (*Scylla serrata*) which is widespread in the tropics was known to have established populations in the southwest following a major recruitment event during the 1999/2000 *La Niña* (Gopurenko et al., 2003), however whether these were self-sustaining breeding populations was not determined. New evidence from studies initiated since the recent marine heat wave suggest that the heat wave may have facilitated range extensions in inshore tropical species *Psammoperca sp.* and *Siganus sp.* (Lenanton et al., in preparation). However despite apparently suitable habitat and sea temperature conditions for a range extension for *A. sexfasciatus* and *A. vaigiensis* at Rottnest Island, no evidence has yet been found to indicate breeding of either species at this location.

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